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A CORRECTION TO THE PP REACTION

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ABSTRACT

These descriptive comments are made to encourage detailed three-body, relativistic, quantum collision calculations for the pp reaction.

In stars, coulomb barrier tunneling, as in the pp reaction, is not a two-body process. Tunneling is mediated by an energetic electron that interacts with the colliding particles. The presence of such an electron lowers the potential barrier and increases the probability of tunneling by orders of magnitude. The solar luminosity can be maintained with a central temperature near 10^7K where the neutrino production rates correspond to the observed rates. Current stellar interior and evolutionary models need substantial revision.

Subject headings: neutrinos — nuclear reactions — stars: interiors — sun: interior

As the pp reaction p + p > d + e^+ + ν can be produced in laboratory accelerators, there is no question that it is a real reaction in which two protons move toward each other with enough energy to quantum-mechanically tunnel through their repulsive coulomb potential and combine. The proton-proton reaction, coulomb-barrier tunneling, and statistical Debye-Hückel electron shielding are discussed in basic texts. However, the conditions in a dense plasma at the center of a star substantially differ from those in an accelerator. At the center of the sun the temperature is of the order of 15×10^6K, the proton density is of the order of 10^{26} protons-cm^{-3}, and the electron density in of the order of 10^{26} electrons-cm^{-3}. Typical velocities are 500 km s^{-1} for protons and 20,000 km s^{-1} for electrons. Slowly moving electrons tend to cluster around slowly moving protons. The electron cluster reduces the proton effective charge by a small amount near the proton and cuts it off completely at a radius of about 10^{-9} cm. Neither fast electrons nor fast protons are aware of a slow proton until they penetrate the shielding electron cluster at which point they are immediately attracted or repelled by the coulomb potential. As the electrons typically move 40 times faster than the protons, the electron-proton collision frequency must be about 40 times the proton-proton collision frequency. A colliding fast proton decelerates from 2000 or 3000 km s^{-1} to 0 km s^{-1} relative velocity by the time it reaches a separation of 10^{-10} cm, which is only 90% of the distance to the target proton. Unless they tunnel, protons are always far apart on a nuclear scale because the nuclear interaction radius is on the order of 10^{-13} cm. A proton-proton collision is a slow process. An electron-proton collision is much faster. A colliding fast electron passes through the shielding electron cluster at, say, 100,000 km s^{-1} and is immediately accelerated toward the central proton. In some collisions the electron passes near the proton, through the volume inaccessible in a proton-proton collision.

A proton can suffer both a proton and an electron collision simultaneously. Such collisions may be infrequent, but they are more probable than tunneling, and they determine the pp reaction rate. When a fast electron penetrates the electron cluster during a proton-proton collision it is attracted by both protons. If the electron approaches from a polar direction with respect to the proton-proton axis, it helps to pull the protons apart and it prevents tunneling. If the electron approaches equatorially, it shields the protons from each other and accelerates them toward each other. Part of the kinetic energy of the electron contributes to the pp reaction. When the electron leaves, the two protons are closer than they would have been on their own and the tunneling probability has greatly increased. The reaction $\mathrm{p} + \mathrm{p} + \mathrm{e} > \mathrm{d} + \mathrm{e} + \mathrm{e}^+ + \nu$ requires lower proton energies than the reaction $\mathrm{p} + \mathrm{p} > \mathrm{d} + \mathrm{e}^+ + \nu$. A solar central temperature of, say, 10×10^6K produces the same energy and neutrino yield as 15×10^6K for the pp reaction without the electron boost. At 10×10^6K pp side chain reactions are much slower than at 15×10^6K and produce the low neutrino rates that are actually observed.

These descriptive comments are made to encourage detailed three-body, relativistic, quantum collision calculations for the pp reaction. Until such calculations become available, the problem can be investigated with solar evolutionary models by making ad hoc increases in the pp reaction rate until the model yields the observed neutrino flux.

Beyond the pp reaction there is much more work. The reactions d + p, ^{3}He + ^{3}He, ^{3}He + ^{4}He, ^{7}Be + p, and ^{7}Li + p are coulomb barrier reactions and also have to be recalculated. The Be and B neutrinos do not come from coulomb barrier reactions so they are not directly affected.

Light element burning occurs at lower temperatures than have been assumed.